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Prediction of Coal Bed Methane Recovery Rate and Its Improvement Measures in Dafosi Mine Field

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Abstract

The recovery rate of coalbed methane (CBM) can reflect the mining situation and the residual gas in coal reservoir. It plays an important role in the calculation of the recoverable resources. This paper mainly uses isothermal adsorption curve method and hydraulic model method to predict recovery rate of CBM. The isothermal adsorption curve method considering desorption lag problem in the prediction process, which is more in line with the actual situation. In the hydraulic model method, the recovery rate of "V" type well is the largest in the early stage. But with the time going on, the recovery rate of multilateral horizontal well is greater than vertical well, "U" type well and "V" type well finally. The factors affecting CBM recovery rate include geological characteristics, development conditions and economic factors. The geological characteristics of coal reservoir are the main factors affecting CBM recovery rate, and corresponding measures can be adopted to improve the recovery rate.

Keywords

Recovery Rate, Isothermal Adsorption Curve Method, Hydraulic Model Method

1. Introduction

CBM recovery rate refers to an economic limit, can be produced by percentage of CBM from CBM reserves in the current engineering and technical conditions, can reflect the mining situation of CBM, and the residual gas in coal reservoir. The recoverable resources of CBM are obtained by multiplying the amount of geological resources by the recovery rate and it is an important basis for investment decision, implementation and adjustment of development plan.

The exploration and development of CBM has been explored and developed for more than 20 years in China. Basically, the two industrial development bases of Qinshui Basin and Ordos Basin have been formed. The development of the CBM industry in recent years, CBM development technology has made great progress, mainly in the deep coal seam fracturing, refracturing, layer fracturing and tectonic coal production measures [1]. These technologies have solved a series of problems, such as pulverized coal blockage. In fact, there are some factors restricting the development of CBM, including geological factors, mining technology factors, industrial policy factors and so on [2]. The structure of CBM reservoir formation is complex in China, and the effect of foreign mining technology is not satisfactory in the development and application of CBM. China's mining technology also has some limitations, resulting in the backwardness of China's CBM industry development.

In view of the low recovery rate of CBM in China, domestic scholars have also conducted relevant research, mainly in gas injection production. Zhao Jin [3] carried out numerical simulation of carbon dioxide injection method for enhancing CBM recovery rate. The results show that carbon dioxide injection can improve the production technology of CBM production and recovery, Shen Jian [4] carried out feasibility analysis about carbon dioxide injection, also got a similar conclusion. Zheng Yuzhu [5] has studied the factors that influence CBM recovery rate and it is considered that the geological characteristics, development conditions and economic factors of coal reservoir have important influence on recovery rate of CBM. At present the study about Dafosi mine field CBM exploitation has mainly carried on the pore characteristics, CBM workability and the occurrence characteristics of CBM. However, there is a lack of research on recovery rate, so it is necessary to study the recovery rate of CBM in Dafosi mine field.

At present, there are few researches on low rank coal recovery rate in China. When using the isothermal adsorption curve to predict recovery rate, it is considered that adsorption and desorption are reversible, and the desorption lag is not taken into consideration [6] [7]. This paper mainly uses the isothermal adsorption curve method and the hydraulic model method to predict the recovery rate in Dafosi mine field, the isothermal adsorption curve method considering desorption lag problem, provides a new idea for prediction of Dafosi mine field recovery rate.

2. Prediction of CBM Recovery Rate in Dafosi Mine Field

2.1. Selection of Prediction Methods

The prediction methods of CBM recovery rate [8] [9] include numerical simulation method, analog method, isothermal adsorption curve method, desorption method and production decline method. The numerical simulation method is based on the CBM production mechanism, through the establishment of geological model and mathematical model, the use of computer to predict the recovery rate. The analog method is used to obtain the recovery rate by comparing with the area where the recovery rate has been obtained. The isothermal adsorption curve method is based on the adsorption of methane on coal in accordance with the Langmuir equation, through calculating the adsorption amount under the waste pressure, the recovery rate is obtained. CBM content is composed of three parts: stripping gas, lost gas and residual gas. Stripping gas and lost gas can be desorbed under natural conditions. The desorption method is used to calculate the recovery rate by calculating the rate of stripping gas and lost gas content. The production decline method is to calculate the recovery ratio through the original coalbed gas content and the abandoned content at the end of exploitation.

The analogy method requires a similar geological condition and has obtained CBM recovery rate areas for comparison. The production decline method is too simple and has low reliability. The prediction of CBM recovery rate by desorption method will be affected by related geological factors. So this paper uses the isothermal adsorption curve method and the hydraulic model method to predict recovery rate. The data of isothermal adsorption curve are easy to obtain, and the predicted recovery rate can be well consistent with the actual production at present stage. The hydraulic model method [10] [11] can well predict the future recovery rate, and has a good prediction and guidance for the future production of CBM. But the two methods have certain limitations, the isothermal adsorption curve method is mainly the determination method of waste pressure is not uniform, may cause the final result of deviation. The hydraulic model method has a long duration, so it is necessary to obtain a large amount of CBM drainage data for calculation.

2.2. CBM Recovery Rate Prediction

2.2.1. Isothermal Adsorption Curve Method

The adsorption of methane on coal is suitable for the Langmuir equation, and the process is a reversible process, which provides a theoretical basis for the prediction of recovery rate by the isothermal adsorption curve method. According to the isothermal adsorption test of coal, with the increase of pressure, the ability of coal to absorb methane is enhanced. When a certain amount of methane is adsorbed on coal, the methane is desorbed and adsorption decreases as the pressure decreases. The formula of CBM recovery rate is expressed by the isothermal adsorption curve method:

$$\eta = 100\times\left(G - V_u\right)/G$$

η—CBM Recovery rate;

G—initial CBM content;

V_u—adsorption capacity of CBM under obsolete pressure.

Samples were collected at site and balanced water experiments were carried out on the samples. After the sample preparation was completed, the methane adsorption/desorption experiments were carried out. Experiments were carried out by using AST-2000 type CBM adsorption/desorption experimental instrument, five experimental temperature points were set at 25˚C, 30˚C, 35˚C, 40˚C, 45˚C. The isothermal adsorption experiment is a repetitive process of prelum-equilibrium-prelum, and the isothermal desorption experiment is a repetitive process of depressurization-equilibrium-depressurization. Experimental equipment automatically collects the pressure, temperature and other experimental data.

The adsorption process was fitted by Langmuir equation [12] [13] [14]. The equation assumes that there is no adsorption molecule interaction in the surface phase, and the probability of each molecule adsorbed is the same, which is a single molecule layer adsorption model. The desorption equation [15] is used to fit the desorption process:

$$V_a = \frac{abP}{1+bP}$$

$$V_b = \frac{abP}{1+bP} + c$$

V_a—adsorption capacity of CBM under pressure P in adsorption process;
V_b—adsorption capacity of CBM under pressure P during desorption;
a—saturated adsorption capacity of coal sample;
b—comprehensive parameters related to adsorption heat;
c—residual adsorption capacity.

The experimental results are shown in **Table 1** and **Figure 1**.

Experience of CBM development in the United States, under the better market conditions, it is feasible and economical to carry out the drainage of coalbed to achieve the overall depressurization of 85%. Therefore, the CBM recovery rate can be calculated by 15% of the original pressure of coalbed, and the calculation results are shown in **Table 2**.

In summary, recovery rate increases with the increase of temperature. When the desorption lag is not considered, the recovery rate is 36.41% to 50.43%. When the delayed desorption is taken into consideration, the recovery rate is only 9.40% to 25.39%.

Table 1. Experimental results of adsorption/desorption of Dafosi NO.4 coalbed equilibrium water sample.

Temperature/˚C	Langmuir fitting			The desorption formula fitting			
	a	b	R^2	a	b	c	R^2
25	11.563	0.448	0.992	8.623	0.701	0.949	0.996
30	11.566	0.396	0.990	8.341	0.619	0.994	0.997
35	11.079	0.382	0.993	8.040	0.597	0.973	0.998
40	10.725	0.374	0.993	7.698	0.543	1.039	0.999
45	10.238	0.382	0.993	7.380	0.568	1.009	0.998

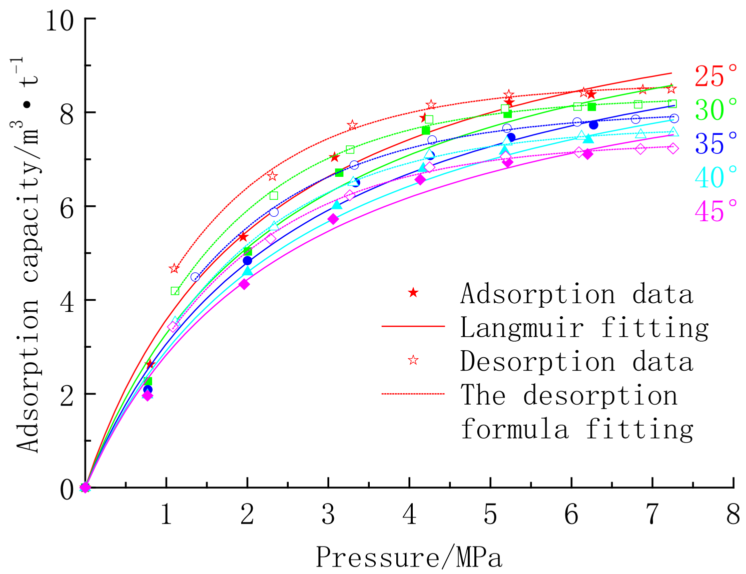

Figure 1. Adsorption/desorption curves of Dafosi No. 4 coalbed equilibrium water samples at different temperatures.

Table 2. Recovery rate of Dafosi No. 4 coalbed equilibrium water sample.

Temperature	V_G	P_O	V_u		Recovery rate/%	
			Langmuir	The desorption formula	Langmuir	The desorption formula
25˚C	3.89	0.6075	2.4737345	3.5244111	36.408	9.398
30˚C	3.89	0.6075	2.2428663	3.2734140	42.343	15.851
35˚C	3.89	0.6075	2.0867796	3.1128512	46.355	19.978
40˚C	3.89	0.6075	1.9856288	2.9484752	48.956	24.204
45˚C	3.89	0.6075	1.9283735	2.9022559	50.427	25.392

2.2.2. Hydraulic Model Method

The method is to approximate the drainage and production process of CBM well into the unsteady flow full pressure well pumping process, using the The is formula to calculate reservoir water conduction coefficient. The influence radius is calculated by Jacob formula during the process of production, a gas production model was established to calculate recovery rate.

1) Calculation of recovery rate in vertical well

Taking No. 1 well in Dafosi mine field as an example, the recovery rate of vertical well is calculated. During the stage of stable production of drainage, the coefficient of water conductivity was calculated by the The is formula, which was 0.0064584m^2/d and the water supply of the aquifer was 0.001. The radius of influence is calculated by Jacob formula, the calculation result is shown in Table 3 and the recovery curve is shown in Figure 2.

2) Calculation of recovery rate in "U" type well

Taking No. 2 well in Dafosi mine field as an example, the recovery rate of "U" type well is calculated. During the stage of stable production of drainage, the

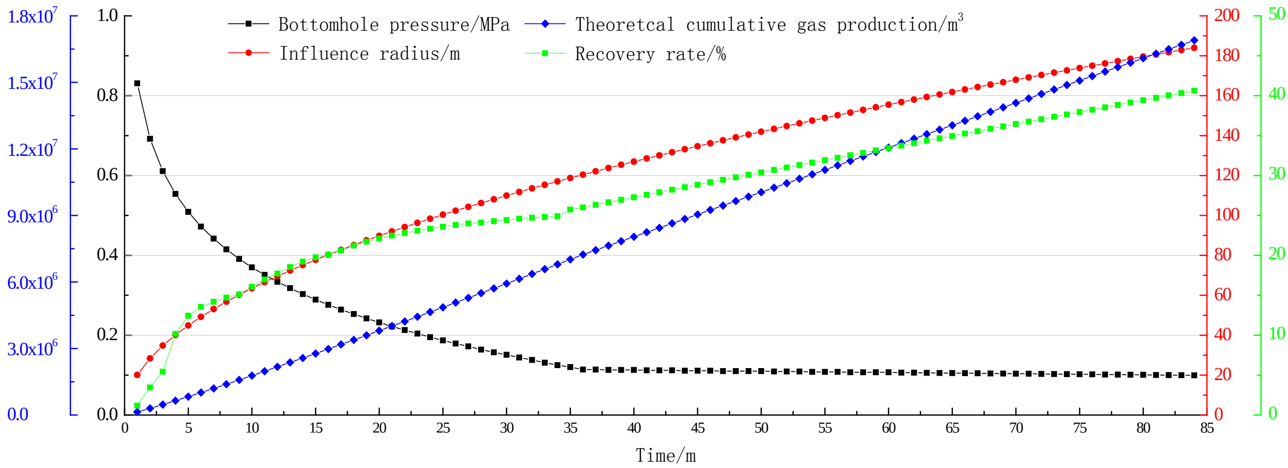

Figure 2. Prediction curve of recovery rate in vertical well.

Table 3. Calculation results of recovery rate in vertical well.

Time/m	Bottomhole pressure P_w/MPa	Influence radius R_e/m	Desorption radius r/m	Theoretical cumulative gas production Q_L/$m^3 \cdot t^{-1}$	Actual cumulative gas production Q_S/$m^3 \cdot t^{-1}$	Recovery rate η/%
1	0.831	20.074	11.52	139314.44	1647.08	1.18
6	0.472	49.171	27.55	1013071.66	137187.46	13.54
12	0.334	69.538	38.66	2171867.88	384884.42	17.72
18	0.253	85.167	47.14	3388736.99	719452.65	21.23
24	0.195	98.342	54.27	4643938.07	1083731.93	23.34
30	0.151	109.95	60.55	5927941.83	1448421.36	24.43
36	0.114	120.44	66.21	7235075.67	1881095.72	26.00
42	0.112	130.09	71.40	8441543.77	2355419.48	27.90
48	0.110	139.08	76.24	9647428.96	2872174.28	29.77
54	0.108	147.51	80.77	10853852.19	3431360.12	31.61
60	0.107	155.49	85.06	12060957.68	4032977.00	33.44
66	0.105	163.08	87.61	13268867.60	4677024.92	35.25
72	0.103	170.33	91.22	14477686.91	5363503.88	37.05
78	0.101	177.29	94.67	15687506.82	6092413.88	38.84
84	0.099	183.98	97.98	16898407.42	6863754.92	40.62

coefficient of water conductivity was calculated by the The is formula, which was 0.02689068m^2/d and the water supply of the aquifer was 0.005. The radius of influence is calculated by Jacob formula, the calculation result is shown in Table 4 and the recovery curve is shown in Figure 3.

3) Calculation of recovery rate in "V" type well

Taking No. 3 well in Dafosi mine field as an example, the recovery rate of "V" type well is calculated. During the stage of stable production of drainage, the coefficient of water conductivity was calculated by the Theis formula, which was

Table 4. Calculation results of recovery rate in "U" type well.

Time/m	Bottomhole pressure P_w/MPa	Influence radius R_e/m	Desorption radius r/m	Theoretical cumulative gas production $Q_L/m^3 \cdot t^{-1}$	Actual cumulative gas production $Q_S/m^3 \cdot t^{-1}$	Recovery rate η/%
1	1.552	16.84	7.08	54433.648	0	0.00
6	0.503	41.25	20.68	709580	33043.44	4.66
12	0.325	58.35	29.35	1551726.9	139273.06	8.98
18	0.252	71.46	35.82	2406545.1	282351.16	12.10
24	0.210	82.52	41.19	3266204.2	490164.24	15.01
30	0.183	92.26	45.86	4128091.3	694397.2	16.82
36	0.163	101.07	50.04	4991033.1	896396.69	17.96
42	0.148	109.17	53.86	5854416.5	1215320.84	20.76
48	0.136	116.71	57.39	6717891.5	1531593.44	22.80
54	0.126	123.79	60.69	7581245.5	1882333.16	24.83
60	0.118	130.49	63.80	8444344.8	2267540.00	26.85
66	0.111	136.86	66.74	9307103.3	2687213.96	28.87
72	0.105	142.94	69.54	10169464.7	3141355.04	30.89
78	0.100	148.78	72.22	11031392.7	3629963.24	32.91
84	0.096	154.40	74.79	11892863.9	4153038.56	34.92

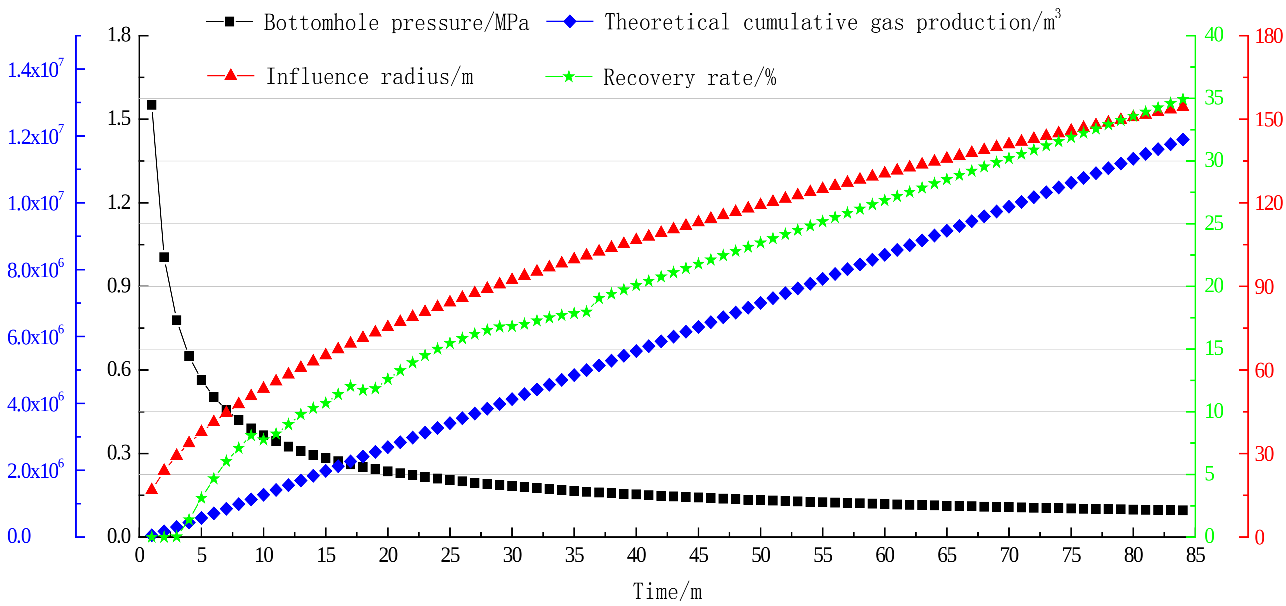

Figure 3. Prediction curve of recovery rate in "U" type well.

0.034841 m^2/d and the water supply of the aquifer was 0.014102. The radius of influence is calculated by Jacob formula, the calculation result is shown in Table 5 and the recovery curve is shown in Figure 4.

4) Calculation of recovery rate in multilateral horizontal well

Taking No. 4 well in Dafosi mine field as an example, the recovery rate of

Table 5. Calculation results of recovery rate in "V" type well.

Time/m	Bottomhole pressure P_w/MPa	Influence radius R_e/m	Desorption radius r/m	Theoretical cumulative gas production $Q_L/m^3 \cdot t^{-1}$	Actual cumulative gas production $Q_S/m^3 \cdot t^{-1}$	Recovery rate η/%
1	1.581	14.62	6.19	40532.34	0.00	0.00
6	0.545	35.81	18.03	525074.04	18306.78	3.49
12	0.152	50.64	26.57	1288303.46	81114.54	6.30
18	0.123	62.02	32.17	1950411.93	115318.03	6.91
24	0.122	71.61	36.72	2591424.48	455720.23	17.59
30	0.121	80.06	40.70	3230203.71	764080.55	23.65
36	0.120	87.71	44.26	3867264.08	1095565.18	28.33
42	0.119	94.73	47.52	4502960.87	1491565.18	33.12
48	0.117	101.27	50.55	5140260.34	1887565.18	36.72
54	0.116	107.42	53.37	5774300.88	2283565.18	39.55
60	0.115	113.23	56.03	6407599.99	2679565.18	41.82
66	0.113	118.75	58.56	7044038.23	3075565.18	43.66
72	0.112	124.03	60.96	7676571.78	3471565.18	45.22
78	0.111	129.10	63.26	8308693.21	3867565.18	46.55
84	0.110	133.97	65.47	8940480.57	4263565.18	47.69

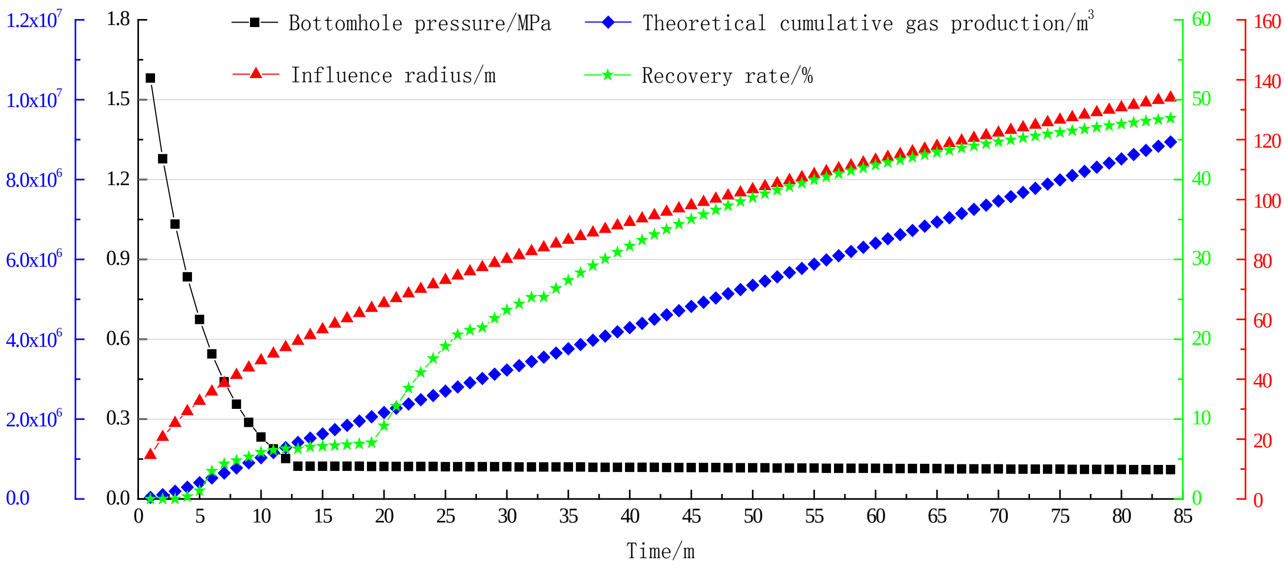

Figure 4. Prediction curve of recovery rate in "V" type well.

multilateral horizontal well is calculated. The radius of influence based on the front vertical well, and the horizontal section is 1500 m. The radius of influence are shown in Table 6, and the recovery curve is shown in Figure 5.

2.2.3. Prediction Analysis

In the foregoing, the isothermal adsorption curve method and the hydraulic

Table 6. Calculation results of recovery rate in multilateral horizontal well.

Time/m	Bottomhole pressure P_w/MPa	Influence radius R_e/m	Desorption radius r/m	Theoretical cumulative gas production Q_L/$m^3 \cdot t^{-1}$	Actual cumulative gas production Q_S/$m^3 \cdot t^{-1}$	Recovery rate η/%
1	2.906	124.33	3.45	28201.15	0.00	0.00
6	2.305	198.23	42.47	1177436.25	0.00	0.00
12	1.524	238.72	88.90	8001914.60	1500.77	0.02
18	1.007	266.70	121.99	17811923.66	241334.18	1.35
24	0.666	288.84	145.91	27815843.73	1415691.28	5.09
30	0.440	307.49	163.89	36989249.73	3661554.51	9.90
36	0.291	323.79	141.93	45106632.79	6672425.60	14.79
42	0.192	338.37	150.94	52234816.44	10238308.40	19.60
48	0.127	351.64	158.48	58527918.45	14600518.40	24.95
54	0.084	363.86	164.97	64148329.28	19759055.60	30.80
60	0.056	375.23	170.67	69238930.34	25713920.00	37.14
66	0.037	385.89	175.77	73916137.79	32465111.60	43.92
72	0.024	395.93	180.43	78271072.6	40012630.40	51.12
78	0.016	405.46	184.72	82373453.24	48356476.40	58.70
84	0.011	414.53	188.72	86275944.36	57496649.60	66.64

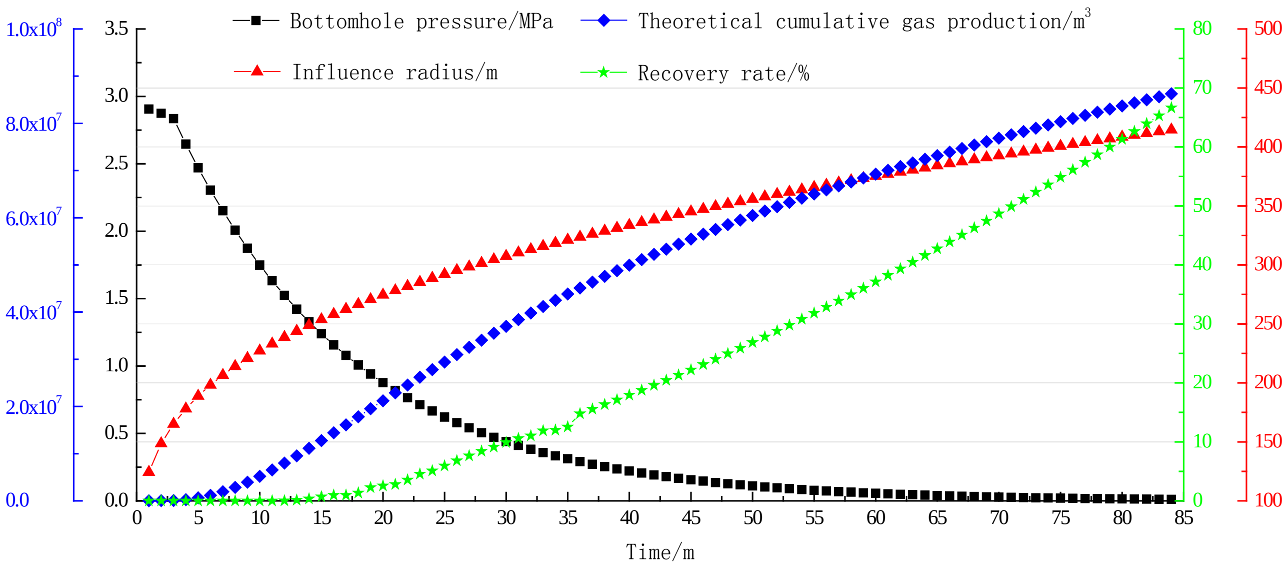

Figure 5. Prediction curve of recovery rate in multilateral horizontal well.

model method are adopted respectively for the recovery efficiency of vertical well. The isothermal adsorption curve method is based on the adsorption/desorption experiment to calculate recovery rate. The hydraulic model rule is based on the original production data and establishes the hydraulic model to calculate recovery rate. Compared with the two methods, the hydraulic model method is more practical.

According to the calculation results of different well types, compared the recovery rate and the comparison results are shown in **Table 7**. It can be found that the recovery rate of "V" type well is the largest in the early stage (3 years), followed by vertical well and "U" type well, and finally the multilateral horizontal well. After 5 years, the recovery rate of "V" type well is still the largest, followed by multilateral horizontal well and vertical well, and finally "U" type well. With the development of production, the recovery rate of multilateral horizontal well is greater than the other three kinds of wells finally.

3. Analysis of Factors Affecting Recovery Rate

The factors affecting CBM recovery rate include geological characteristics, development conditions and economic factors [16]. The geological characteristics of coal reservoir are the main factors affecting CBM recovery rate, including coal rank, depth, adsorption characteristics, permeability and gas content [17]. The effect of gas content on recovery rate is due to the presence of waste pressure. When the waste pressure is determined, for coalbed with the same adsorption capacity, residual adsorption capacity is determined, so when the gas content is higher, the recovery rate of CBM is higher. When the adsorption capacity is different and the gas content is uniform, residual adsorption capacity is higher, the recovery rate of CBM is lower. The permeability is mainly rely on the changing nature of the coalbed to change the recovery rate, in the case of low permeability, desorption-diffusion-percolation can't be formed in a large range, resulting in low gas production and the recovery rate is not up to the expected result. The influence factors of coal rank, depth and reservoir pressure affect the adsorption characteristics, permeability and other physical properties of coal under the combined action, and have a certain influence on recovery rate of CBM.

Table 7. Contrast of recovery rate.

CBM well type	Production time/y	Recovery rate/%
Vertical well	3	26.00
	5	33.44
	7	40.62
"U" type well	3	17.96
	5	27.19
	7	34.92
"V" type well	3	28.33
	5	41.82
	7	47.69
Multilateral horizontal well	3	14.79
	5	37.14
	7	66.64

4. Measures for improving CBM Recovery Rate in Dafosi Mine Field

According to the factors affecting CBM recovery rate, the corresponding measures can be taken to improve recovery rate, mainly in permeability, adsorption capacity and development conditions [18] [19] [20] [21].

CBM reservoir has the characteristics of low pressure, low permeability and low saturation. The gas exists mainly in the adsorbed state, and its output is a complex process of desorption-diffusion-percolation. China's coalbed is low pressure and less saturated, which is the reason China's CBM overall recovery rate is not large. Through artificial modification of physical properties of coal reservoir, recovery rate of CBM can be improved, and the main methods are hydraulic fracturing and gas injection production.

After hydraulic fracturing, coalbed interior will appear a plurality of extending far crack. In the process of drainage and depressurization, the range of pressure reduction can be increased, thus making it more desorption of CBM, increasing gas production of CBM well. Gas injection production technology mainly uses coal to adsorb CO_2 stronger, and displaces CH_4 in the void of coal matrix. By injecting CO_2 and other gas into coal reservoir and coal reservoir saturation will be increased, the desorption rate of CBM will be accelerated.

Drilling technology can also increase CBM recovery rate, mainly in multilateral horizontal well drilling technology. The resistance of fluid in horizontal well is relatively small, the branch hole and coalbed cleat intersect each other, so that the cleat and fracture of coalbed are more unblocked, and the desorption range of CBM is increased. The permeability of Dafosi mine field coal reservoir is good, the hardness of coalbed is large, and the discharge area of CBM well is large. During the development of multilateral horizontal well, the discharge area of each branch can be disturbed in a short time, so that CBM between the branches can be fully desorbed and migrated to the wellbore.

5. Conclusions

1) In the isothermal adsorption method, the desorption hysteresis is well solved by the desorption formula, and the calculated recovery rate is lower than that calculated by Langmuir equation, which is in line with the actual situation. The recovery rate of "V" type well is the biggest in the early stage of hydraulic model, but with the development of production, the recovery rate of multilateral horizontal well is greater than the other three kinds of wells finally.

2) The factors affecting CBM recovery rate include geological characteristics, development conditions and economic factors. The geological characteristics of coal reservoir are the main factors affecting CBM recovery rate, including coal rank, depth, adsorption characteristics, permeability and gas content.

3) Through the hydraulic fracturing and gas injection production, the physical properties of coal reservoir can be improved to improve recovery rate, and drilling technology, such as multilateral horizontal well drilling technology, can be

used to improve recovery rate of CBM.

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